

Influence of XUV radiation on P v ionization fraction in hot star winds

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ABSTRACT

Different diagnostics of hot star wind mass-loss rates provide results that are difficult to reconcile with each other. The widely accepted presence of clumping in hot star winds implies a significant reduction of observational mass-loss rate estimates from diagnostics that depend on the square of the density. Moreover, the ultraviolet P v resonance lines indicate a possible need for even stronger reduction of hot star mass-loss rates, provided that P v is a dominant ionization stage of phosphorus at least in some hot stars. The latter assumption is challenged by a possible presence of the XUV radiation.

Here we study the influence of the XUV radiation on the P v ionization fraction in the hot star winds. By a detailed solution of the hydrodynamical, radiative transfer, and statistical equilibrium equations we confirm that sufficiently strong XUV radiation source may decrease the P v ionization fraction, possibly depreciating the P v lines as a reliable mass-loss rate indicator. On the other hand, the XUV radiation influences also the ionization fraction of heavier ions that drive the wind, leading to a decrease of the wind terminal velocity. Consequently, we conclude that the XUV radiation alone can not bring theory and observations in accord.

We fit our predicted wind mass-loss rates by a suitable formula and compare the results with the observational mass-loss rate diagnostics. We show that for supergiants and giants the theoretical predictions do not contradict the mass-loss rate estimates based on X-ray line profiles or density squared diagnostics. On the other hand, for main-sequence stars the predicted mass-loss rates are still significantly higher than that inferred from P v or X-ray lines. This indicates that the “weak wind problem” recently detected in low-luminosity main-sequence stars may occur to some extent also for the stars with higher luminosity.

Key words: stars: winds, outflows – stars: mass-loss – stars: early-type – hydrodynamics – X-rays: stars

1 INTRODUCTION

Mass-loss plays an important role in the massive star evolution. Most of the mass of massive stars is lost during their evolution from zero-age main sequence to the final remnant. Different processes contribute to the mass loss in individual evolutionary phases. These processes include line-driven winds during hot evolutionary stages (Puls et al. 2008a), decretion disks in fast-rotating stars (Lee et al. 1991; Okazaki 2001), LBV-type of explosions in hot supergiants (Smith & Owocki 2006), dust-driven winds in cool supergiants (Woitke 2006), and a final supernova explosion (Umeda & Nomoto 2008). Consequently, estimates of amount of mass lost per unit of time (mass-loss rate) as a functions of stellar parameters belong to one of the most important ingredients of evolutionary models.

Unfortunately, the uncertainties in modern mass-loss rate de-

terminations significantly affect the evolutionary models of massive stars. In the case of the line-driven wind of hot stars, these uncertainties seem to be mostly connected with the occurrence of small-scale inhomogeneities (Hamann et al. 2008). The inhomogeneities are typically divided into three different groups (microclumping, porosity, and vorosity) according to their influence on the spectral features, although they may be caused by the same structure observed in different wavelengths. Microclumping (also frequently referred to as clumping), that accounts for the enhanced density in the optically thin inhomogeneities, can be most easily incorporated in the wind models (e.g., Hamann & Gräfener 2004; Puls et al. 2006; Krtička et al. 2008). Microclumping affects the ionization equilibrium via enhanced recombination, consequently it influences the radiative transfer only indirectly (Abbott et al. 1981). On the other hand, porosity (also referred to as macroclumping) accounts for the nonnegligible optical depth of inhomogeneities (which may become optically thick), and directly influences the

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radiative transfer (Oskinova et al. 2007; Sundqvist et al. 2011; Šurlan et al. 2012a). Vorosity affects the line profiles, and it is connected with the different Doppler shifts of individual inhomogeneities (Owocki 2008). From the point of view of mass-loss rate predictions, the inhomogeneities may affect the ionization fractions of wind driving ions (Krtićka et al. 2008; Muijres et al. 2011), or they may lead to the decrease of the wind mass-loss rate due to the base turbulence (Lucy 2007; Krtićka & Kubát 2010).

There could be a simple observational solution of the mass-loss rate determination problem: to find such observational characteristic that is not affected by the wind inhomogeneities. There are two potential candidates for such convenient observables: the X-ray radiation (either line profiles or the continuum flux distribution, MacFarlane et al. 1991; Owocki & Cohen 2001; Ignace & Gayley 2002; Cohen et al. 2011a), and unsaturated resonance line profiles. The latter case is fulfilled for trace elements, and especially interesting is the P v ion (Crowther et al. 2002; Massa et al. 2003; Fullerton et al. 2006). However, even these characteristics face some problems. The opacity in the X-ray domain scales mostly linearly with the density, consequently its effect on the X-ray diagnostics should be in principle possible to model in a straightforward way. Indeed, the observations of mostly symmetric X-ray line profiles, that are not strongly affected by absorption, indicate low wind mass-loss rates (Waldron & Cassinelli 2001; Cohen et al. 2010; Gagné et al. 2011). These results are, however, challenged by a possible effect of the porosity on the X-ray opacity (Feldmeier et al. 2003; Oskinova et al. 2006). Note that there is not a general consensus on this problem (Oskinova et al. 2012; Owocki et al. 2012).

Here we concentrate mostly on the other promising observational characteristic, i.e., on the P v resonance lines. The weakness of observed P v lines also indicates low mass-loss rates of hot star winds (Fullerton et al. 2006). However, the ionization fraction of P v may be modified by the effect of clumping (Puls et al. 2008b; Krtićka et al. 2008). Additional changes of the P v ionization fraction may be caused by the influence of X-rays. Although our previous calculations indicated that P v ionization fraction is not strongly affected by X-rays (Krtićka & Kubát 2009), Waldron & Cassinelli (2010) argued that the extreme ultraviolet radiation (hereafter XUV) may affect P v ionization fractions. Since the work of Waldron & Cassinelli (2010) was based on rather simplified ionization estimates and the calculations presented in Krtićka & Kubát (2009) were done without enhanced XUV radiation, we decided to fill this gap and we apply our NLTE wind models to study the influence of the XUV radiation (parameterized in a convenient way) on the P v ionization fraction. The XUV region is defined here as the energy from interval 54.4 eV (He II edge) to 124 eV.

2 WIND MODELS

For our calculations we use NLTE wind models of Krtićka & Kubát (2010) with a comoving frame (CMF) line force. Our models assume stationary, and spherically symmetric wind flow. They enable us to selfconsistently predict wind structure just from the stellar parameters (the effective temperature, mass, radius, and chemical composition). The line radiative force is calculated directly by summing the contribution from individual atomic transitions, i.e. we do not use the CAK line force parameters.

The ionization and excitation state of the considered elements is derived from the statistical equilibrium (NLTE) equations. Ionic models are either adopted from the TLUSTY grid of model stellar

Table 1. Stellar parameters of the model grid

	model	T_{eff} [K]	R_* [R_{\odot}]	M [M_{\odot}]	\dot{M} [$M_{\odot} \text{ year}^{-1}$]
main sequence	300-5	30 000	6.6	12.9	9.5×10^{-9}
	325-5	32 500	7.4	16.4	9.8×10^{-9}
	350-5	35 000	8.3	20.9	4.6×10^{-8}
	375-5	37 500	9.4	26.8	1.8×10^{-7}
	400-5	40 000	10.7	34.6	6.4×10^{-7}
	425-5	42 500	12.2	45.0	1.2×10^{-6}
giants	300-3	30 000	13.1	19.3	8.7×10^{-8}
	325-3	32 500	13.4	22.8	1.8×10^{-7}
	350-3	35 000	13.9	27.2	4.5×10^{-7}
	375-3	37 500	14.4	32.5	1.0×10^{-6}
	400-3	40 000	15.0	39.2	1.8×10^{-6}
	425-3	42 500	15.6	47.4	2.9×10^{-6}
supergiants	300-1	30 000	22.4	28.8	4.7×10^{-7}
	325-1	32 500	21.4	34.0	7.7×10^{-7}
	350-1	35 000	20.5	40.4	1.3×10^{-6}
	375-1	37 500	19.8	48.3	2.3×10^{-6}
	400-1	40 000	19.1	58.1	3.0×10^{-6}
	425-1	42 500	18.5	70.3	3.7×10^{-6}

atmospheres (Lanz & Hubeny 2003, 2007) or are created by us using the data from the Opacity and Iron Projects (Seaton et al. 1992; Hummer et al. 1993). For phosphorus we employed data described by Pauldrach et al. (2001). Auger photoionization cross sections from individual inner-shells were taken from Verner & Yakovlev (1995, see also Verner et al. 1993), and Auger yields were taken from Kaastra & Mewe (1993). The emergent surface flux is taken from H-He spherically symmetric NLTE model stellar atmospheres of Kubát (2003, and references therein). For our wind calculations we assume a solar chemical composition after Asplund et al. (2009).

The radiative force is calculated using the solution of the spherically symmetric CMF radiative transfer equation (Mihalas et al. 1975). The corresponding line data were extracted in 2002 from the VALD database (Piskunov et al. 1995, Kupka et al. 1999). The radiative cooling and heating terms are derived using the electron thermal balance method (Kubát et al., 1999). For the calculation of the radiative force and the radiative cooling and heating terms we use occupation numbers derived from the statistical equilibrium equations. The hydrodynamical equations, i.e., the continuity equation, equation of motion with the CMF line force, and the energy equation with radiative heating and cooling included are solved iteratively to obtain the wind density, velocity, and temperature structure. The wind mass-loss rate is derived from the critical condition (Castor, Abbott & Klein 1975) generalized for the case of CMF line force. The derived mass-loss rate corresponds to the maximum one for which smooth transonic solution can be obtained (Poe et al. 1991).

For our study we selected O star model grid with the effective temperatures in the range 30 000 – 42 500 K. The parameters for the stars with given effective temperatures were obtained using relations derived by Martins et al. (2005a) for main-sequence stars, giants, and supergiants (see Table 1).

Our new models predict slightly lower mass-loss rate than our older models (Krtićka et al. 2009) due to inclusion of line overlaps via the solution of the CMF radiative transfer equation (Krtićka & Kubát 2010). The mass-loss rate predictions for all

models are also listed in the Table 1. We fitted these mass-loss rate predictions as

$$\log \left(\frac{\dot{M}}{10^{-6} M_{\odot} \text{ year}^{-1}} \right) = (a + a_1 l) \log \left(\frac{L}{10^6 L_{\odot}} \right) + b + b_1 l, \quad (1)$$

where l is the luminosity class (i.e., 1 for supergiants, 3 for giants and 5 for main-sequence stars), and

$$\begin{aligned} a &= 2.040, & a_1 &= -0.018, \\ b &= 0.552, & b_1 &= 0.068. \end{aligned} \quad (2)$$

We compared formula Eq. (1) with mass-loss rate predictions of Vink et al. (2001) calculated for the mass-fraction of heavier elements $Z = 0.0134$ (note that the solar mass-fraction of heavier elements assumed by Vink et al. (2001) is different, $Z = 0.0194$, Anders & Grevesse 1989). On average our models predict slightly lower mass-loss rates by a factor of about 1.7. Formula Eq. (1) shows an excellent agreement with Pauldrach et al. (2012) models A⁺/A[−] of ζ Pup, while the predictions of our formula are by a factor of about 1.6 lower than the mass-loss rate of models D⁺/D[−].

3 ADDITIONAL X-RAY/XUV RADIATION SOURCE

We include an additional source of X-ray/XUV radiation into our wind models. For this purpose we use the X-ray emissivity $\eta_X(r, \nu)$ (Krtićka et al. 2009, Eq. 11), which was derived using the numerical simulations of wind instability (Feldmeier et al. 1997). This additional high energy emission starts at the radius $2R_*$, and integrates the emission from the gas with different shock temperatures as derived from hydrodynamical simulations. In our approach the X-ray emission lines, which mostly contribute to the high energy emission in hot stars, are not treated individually, but they are summed over selected wavelengths. This approach is fully satisfactory because most of these lines are optically thin in the cold wind, consequently the X-ray emission lines influence the wind ionization equilibrium via Auger and direct photoionization only (e.g., MacFarlane et al. 1991).

The original expression for the X-ray emissivity $\eta_X(r, \nu)$ is modified to test the influence of the XUV radiation on the wind ionization. We introduce a nondimensional free parameter β_{XUV} that scales the original X-ray emissivity $\eta_X(r, \nu)$ in the XUV region. This region includes frequencies $\nu_{XUV}^{\min} \leq \nu \leq \nu_{XUV}^{\max}$, where ν_{XUV}^{\min} is the He II ionization threshold (54.4 eV), and we selected $\nu_{XUV}^{\max} = 3 \times 10^{16} \text{ s}^{-1}$, which corresponds to 124 eV. The modified X-ray emissivity included in our models is therefore given by

$$\tilde{\eta}_X(r, \nu) = \begin{cases} 0, & \nu < \nu_{XUV}^{\min}, \\ \beta_{XUV} \eta_X(r, \nu), & \nu_{XUV}^{\min} < \nu < \nu_{XUV}^{\max}, \\ \eta_X(r, \nu), & \nu > \nu_{XUV}^{\max}. \end{cases} \quad (3)$$

For $\beta_{XUV} = 0$ the additional XUV emission is not considered at all and only additional X-ray ionization source is included, whereas $\beta_{XUV} > 1$ corresponds to enhanced source of the XUV emission.

4 C v IONIZATION FRACTION AND ADDITIONAL IONIZATION SOURCES

The presence of lines of ions with higher degree of ionization (for example C v) is often used (e.g., by Waldron & Cassinelli 2010) as an argument for the existence of additional XUV or X-ray ionization source. Although it is generally true that additional ionization source shifts the degree of ionization, due to the complexity of the

processes involved we can not claim that the presence of a particular ion is caused exclusively by radiation at a chosen frequency.

As an example let us study the ionization ratio of C IV and C v. Assuming that the population of the ground levels of these ions dominate, i.e. that we can neglect population of excited states, the ionization balance between the C IV ion (N_4 is its number density) and C v ion (number density N_5) follows from the equations of statistical equilibrium (Mihalas 1978) as

$$N_4 R_{45} - N_5 R_{54} = 0, \quad (4)$$

where we took into account only the radiative ionization and recombination (collisional transitions are neglected). The radiative ionization rate

$$R_{45} = 4\pi \int_{\nu_4}^{\infty} \frac{\alpha_4(\nu)}{h\nu} J(\nu) d\nu, \quad (5a)$$

and the radiative recombination rate

$$R_{54} = 4\pi \left(\frac{N_4}{N_5} \right)^* \int_{\nu_4}^{\infty} \frac{\alpha_4(\nu)}{h\nu} \left[\frac{2h\nu^3}{c^2} + J(\nu) \right] e^{-\frac{h\nu}{kT}} d\nu, \quad (5b)$$

where asterisk denotes LTE values and $\alpha_{4,\nu}$ is the photoionization cross-section. Replacing the integrals in Eq. (5) with values at the ionization frequency ν_4 and taking into account that for a considered spectral range $2h\nu^3/c^2 \gg J(\nu)$, we derive from Eq. (4)

$$\frac{N_5}{N_4} = J(\nu_4) \frac{c^2}{2h\nu_4^3} \left(\frac{N_5}{N_4} \right)^* e^{\frac{h\nu_4}{kT}}. \quad (6)$$

Using the Saha-Boltzmann equation, the fraction $(N_5/N_4)^*$ can be eliminated and the latter equation can be further simplified (assuming unity ionic partition function) to

$$\frac{N_5}{N_4} = \frac{c^2}{h^4 \nu_4^3} (2\pi m_e kT)^{3/2} \frac{J(\nu_4)}{N_e}, \quad (7)$$

where N_e is the electron density. From this equation it seems that indeed the ionization ratio is directly proportional to the mean radiation intensity J at a given ionization frequency ν_4 . Using values appropriate for the model 350-1 at roughly $2.3 R_*$, we obtain in absence of additional ionization sources for $\nu_4 = 1.6 \times 10^{16} \text{ Hz}$, $T = 22000 \text{ K}$, $N_e = 3 \times 10^9 \text{ cm}^{-3}$, and $J(\nu_4) = 8 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}$ from Eq. (7) the ionization ratio $N_5/N_4 \approx 7 \times 10^{-4}$. This indicates low ionization fraction of C v there. However, from our full NLTE models, which consider reliable model ions, we obtain for the same location $N_5/N_4 \approx 0.2$.

The reason is that statistical equilibrium equations are quite complex in hot star winds and their oversimplification using handy equations like Eq. (7) may lead to incorrect results. In the particular case of C v ionization fraction, the most important ionization process is not that from the ground level, but from the less populated upper levels, which are closely coupled with the ground level by a strong bound-bound transitions. This information can be obtained only solving the equations of statistical equilibrium.

Consequently, a care has to be taken when making the conclusions about the existence of additional ionization source just from the observations of C v lines. The same comment is valid also for N v lines (Pauldrach 1987; Krtićka & Kubát 2009).

5 INFLUENCE OF XUV RADIATION ON P v IONIZATION FRACTION AND WIND MODELS

Let us now turn our attention to P v. Without additional XUV sources, for $\beta_{XUV} = 0$ our models agree with the conclusions of

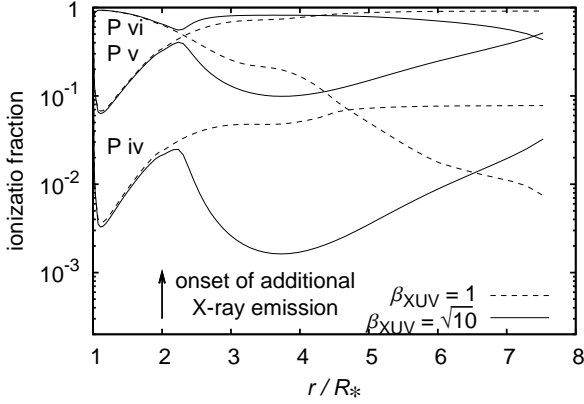


Figure 1. Ionization fraction of individual phosphorus ions in the model 400-1 with different XUV sources

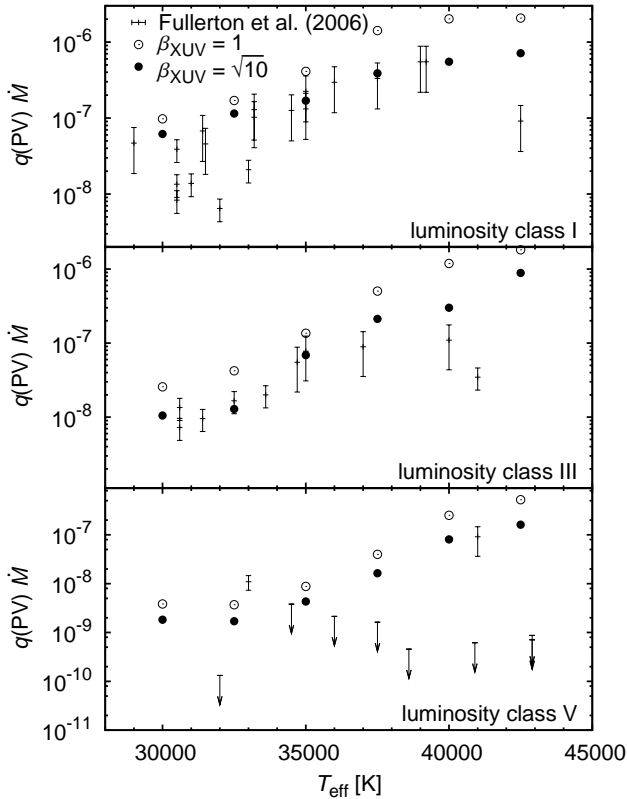


Figure 2. Comparison of predicted product of averaged P V ionization fraction and the wind mass-loss rate $q(\text{P V})\dot{M}$ calculated with $\beta_{\text{XUV}} = 1$ (empty circles) and $\beta_{\text{XUV}} = \sqrt{10}$ (full circles) with results derived from observations (Fullerton et al. 2006, errorbars and upper limits) as a function of stellar effective temperature. The results for different luminosity classes are separated into individual graphs.

Krtićka & Kubát (2009), according to which the X-rays do not significantly influence the ionization fraction of P V. Only the ionization fraction of P VII (and P VI in cooler stars) is significantly influenced by the X-rays, while P V stays to be one of the dominant ionization stages.

The inclusion of XUV radiation (with $\beta_{\text{XUV}} = 1$, see Fig. 1) leads to a slight reduction of the P V ionization fraction to roughly 60% of its value calculated without XUV radiation ($\beta_{\text{XUV}} = 0$). This indicates that a stronger XUV source may lead to a significant reduction of P V ionization fraction. Indeed, the P V ionization fraction is significantly reduced in the models with $\beta_{\text{XUV}} = \sqrt{10}$, as shown in Fig. 2. Here we plot the product of P V ionization fraction and wind mass-loss rate $q(\text{P V})\dot{M}$ averaged over radii $2 \leq r/R_* \leq \min(5, x_{\text{max}})$ with x_{max} being the radius of the outer model boundary (in units of R_*).

The comparison of predicted P V ionization fractions and those derived from observations by Fullerton et al. (2006) in Fig. 2 supports the suggestion of Waldron & Cassinelli (2010) that enhanced source of XUV radiation leads to a reduction of the P V ionization fraction. There is a good agreement between the product $q(\text{P V})\dot{M}$ for the parameter $\beta_{\text{XUV}} = \sqrt{10}$ and the observational one (determined by Fullerton et al. 2006) for supergiants and giants. On the other hand, the results for main-sequence stars are ambiguous. While for main-sequence stars with detected P V line there is a good agreement with observations even without additional X-ray/XUV source, for stars with only upper limit of $q(\text{P V})\dot{M}$ available even a very strong X-ray/XUV source does not bring the predictions and observations into agreement. Such disagreement can be a signature of a “weak wind problem” (e.g. Bouret et al. 2003; Martins et al. 2005b).

Waldron & Cassinelli (2010) argued that due to a unique distribution of XUV radiation, where the strongest XUV emission lines have energies lower than the S V edge (72.7 eV), the XUV radiation affects the ionization fraction of P V and not that of S V. This effect might not be fully included in our models, where the XUV emission lines are summed over a corresponding wavelength region. This ensures that the total line emissivity is properly taken into account, but some subtle effects of line distribution may be missing. To test the effect of XUV line distribution, we calculated additional models with XUV emission present only for energies lower than 72 eV. These models confirm that with a convenient distribution of XUV emission the influence of XUV radiation on P V ionization fraction is more significant than on S V (roughly by a factor of 2). However, even the ionization fraction of S V is affected by XUV radiation with energies lower than the ionization energy of S V due to the ionization from higher levels of S V, especially from the relatively strongly populated second level $3s3p^3\text{P}$ with a ionization energy 62.4 eV. This is a similar situation to C V ionization fraction discussed in Sect. 4.

However, despite the promising results derived for P V in giants and supergiants, a detailed inspection of our models (which consistently include *all* possible driving ions) shows that there exists one additional (and natural) effect of the XUV radiation. Phosphorus is a trace element and changes of its ionization balance have only negligible effects on the radiation force. However, also many ionization states of non-trace elements, which are the wind drivers, are depopulated by XUV radiation. These ions include C IV (ionization energy $E_{\text{ion}} = 64.5$ eV), N IV ($E_{\text{ion}} = 77.5$ eV), O III ($E_{\text{ion}} = 54.9$ eV), O IV ($E_{\text{ion}} = 77.4$ eV), and Si IV ($E_{\text{ion}} = 45.1$ eV). This causes drastic changes in the line force accelerating the whole wind. Consequently, the wind becomes overionized and the radiation driving by higher ionization states becomes inefficient

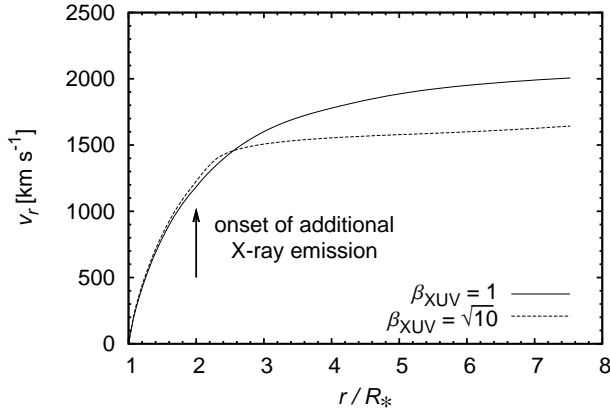


Figure 3. Influence of XUV radiation on the wind radial velocity in the model 400-1.

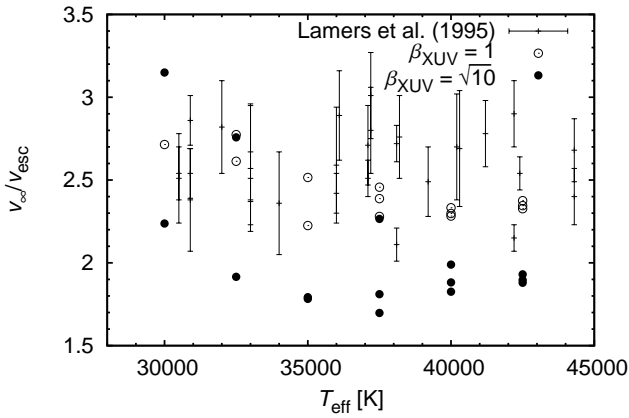


Figure 4. Comparison of predicted ratio of the wind terminal velocity and escape velocity calculated with $\beta_{\text{XUV}} = 1$ (empty circles) and $\beta_{\text{XUV}} = \sqrt{10}$ (full circles) with results derived from observed v_∞ (Lamers et al. 1995).

due to their insufficient line opacity. This causes significant lowering of the radiative force. Consequently, the wind overionization leads to wind stagnation that starts roughly at the radius where the XUV radiation is switched on in our models, i.e., at $r = 2R_*$ (see Fig. 3). In our calculations models of giants and supergiants of all spectral types and main sequence stars with $T_{\text{eff}} \gtrsim 35\,000$ K are subject to this effect.

Such stagnation would be observationally manifested by a decrease of the wind terminal velocity. In Fig. 4 we plot the ratio of the wind terminal velocity to the escape velocity v_∞/v_{esc} from our models in comparison with observational results. For a weak additional XUV source $\beta_{\text{XUV}} = 1$ the predicted v_∞/v_{esc} nicely reproduces the observed results (Krtićka & Kubát 2009). However, for a stronger XUV source $\beta_{\text{XUV}} = \sqrt{10}$ that reproduces the observed P V ionization fractions, the predicted v_∞/v_{esc} is significantly lower than that based on observational results. This disagreement could be in principle partially compensated in models with an onset of additional XUV emission farther from the stellar surface, however this is supported neither by models (Feldmeier et al. 1997) nor by the observations (e.g., Waldron & Cassinelli 2001;

Leutenegger et al. 2006; Cohen et al. 2011a). By contrast, the onset of XUV emission closer to the star suggested by observations leads to even lower wind terminal velocity, which does not agree with observations.

6 DISCUSSION: WIND MASS-LOSS RATES – THEORY MEETS OBSERVATIONS?

The question of correct mass-loss rate determination is the most important one of any wind theory and observation. Despite a significant progress in line driven wind theory and especially in our understanding of the radiative transfer in structured winds in recent years (Sundqvist et al. 2011; Šurlan et al. 2012a), the answer to this question is not unambiguously solved. Concerning the P V ionization fractions studied here, a reduction of mass-loss rate predictions by a factor of about 3 is necessary to bring the observation of giants and supergiants and theory into agreement (assuming $\beta_{\text{XUV}} = 1$ not to violate the observed terminal velocities).

6.1 P V ionization fractions with XUV emission and clumping

Puls et al. (2008b) proposed that the problem of weak P V lines is caused by microclumping (see also Crowther et al. 2002; Krtićka et al. 2008). High density inside the clumps favors the recombination leading to decrease of P V ionization fraction. We tested if the combination of microclumping and additional XUV source does not bring observations and theory into agreement. For this purpose we calculated other models, in which we both allowed for additional XUV emission and took into account the influence of higher wind density in the clumps on the NLTE equations (as in Krtićka et al. 2008). Within this microclumping approach the inhomogeneities directly affect the ionization equilibrium only and do not influence the radiative transfer due to porosity. We assume that the clumping starts above the critical point at the same radius as the additional X-ray emission, i.e., at $2R_*$. In this case the clumping does not affect the predicted mass-loss rates (cf. Krtićka et al. 2008).

Our models show that clumping does not bring observations and theory into agreement. Clumping has an opposite effect than additional XUV source decreasing the wind ionization. Therefore, with microclumping (and XUV emission) the phosphorus ionization fractions disagree with values derived from observations, while the higher radiative force (due to lower ionization) provides better agreement with observed terminal velocities. We were unable to find such combination of parameters (describing additional XUV emission and microclumping) that would provide both phosphorus ionization fractions and terminal velocities in agreement with observations. On the other hand, the porosity, i.e., the effect of wind structure on the line formation (Oskinova et al. 2007; Sundqvist et al. 2011; Šurlan et al. 2012b) is the more promising one for the explanation of the remaining discrepancy between theoretical and observed P V line profiles.

6.2 Mass-loss rates from X-ray diagnostics

The situation is a bit different in the case of the mass-loss rate derived from X-ray line profiles than in the case of P V line profiles. The shape of X-ray line profiles may also imply low mass-loss rates in hot stars (Waldron & Cassinelli 2001). Contrary to P V line profiles, the microclumping does not affect the shape of X-ray line profiles. However, the influence of porosity is still debated

Table 2. Wind mass-loss rates estimated for individual stars from X-ray diagnostics compared with our prediction after Eq. (1).

Star	Sp. type	$\log(L/1 L_{\odot})$	\dot{M} [$10^{-6} M_{\odot} \text{ year}^{-1}$]		Source (luminosities and X-ray mass-loss rates)
			X-ray diagnostics	prediction	
HD 93129A	O2 If	6.17	6.8 ± 2.5	9.2	Cohen et al. (2011a), Repolust et al. (2004)
ζ Pup	O4If	5.86	3.5 ± 0.3	2.2	Cohen et al. (2010), Puls et al. (2006)
HD 93250	O4IIIIf	5.95	1.4 ± 0.5	6.2	Gagné et al. (2011)
9 Sgr	O4V	5.67	0.34	1.8	Cohen et al. (2011b), Martins et al. (2005a)

(Oskinova et al. 2012; Owocki et al. 2012). Moreover, these determinations involve some simplifying approximations, for example, the constant ionization structure of the ambient cool wind.

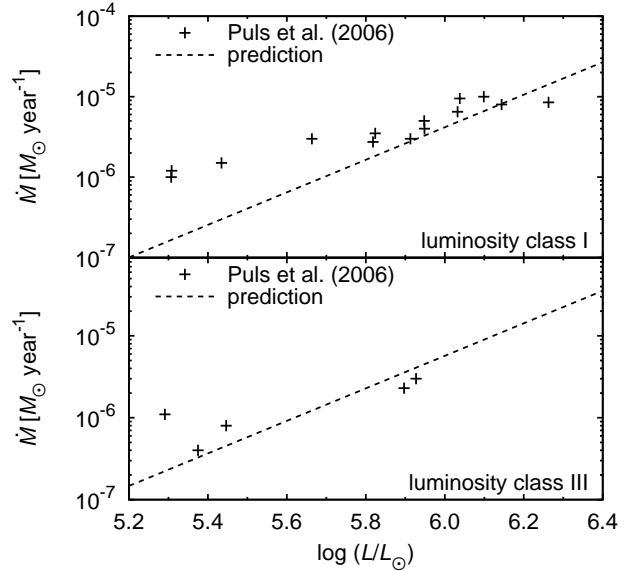
In Table 2 we compare the mass-loss rates calculated using formula Eq. (1) with those derived from X-ray line profiles and from continuum X-ray absorption in the case of HD 93250. The comparison may be biased, because HD 93250 and 9 Sgr are binaries and show peculiar features, including enhanced or non-thermal radio emission or colliding winds (Leitherer et al. 1995; Rauw et al. 2002; Sana et al. 2011; Gagné et al. 2011; Rauw et al. 2012). Note also that the mass-loss rate in the case of ζ Pup was derived from observations assuming non-solar chemical composition (Cohen et al. 2010), while our models assume solar chemical composition.

The results shown in Table 2 show that there is a good agreement between wind mass-loss rates derived from observations and theory for the two supergiants, while for the other two non-supergiant stars predicted rates overestimate the observed ones by a factor of about 5. This result may reflect a similar dichotomy between supergiant and main-sequence mass-loss rates found from P V ionization fractions (see Fig. 2).

6.3 ρ^2 diagnostics as upper limit to the mass-loss rates

The $H\alpha$ emission line and infrared (or radio) continua belong to traditional mass-loss rate indicators. However, the amount of $H\alpha$ emission or infrared excess is not directly proportional to the wind density ρ , but to its square ρ^2 (e.g., Puls et al. 2008b). The structured (clumped) wind with lower mass-loss rate may mimic spectral features of the homogeneous wind with higher mass-loss rate. Consequently, the $H\alpha$ emission line or infrared continua may provide only upper limits to the mass-loss rate (Puls et al. 2006), since they give values which correspond to a homogeneous wind. The predicted mass-loss rates should be lower than that derived from ρ^2 diagnostics (i.e., $H\alpha$ emission line or infrared continua).

In Fig. 5 we plot the predicted mass-loss rates calculated using Eq. (1) as a function of stellar luminosity in comparison with observational upper limits derived from ρ^2 diagnostics by Puls et al. (2006). The luminosity of stars from this observational sample was derived using the stellar parameters taken from Puls et al. (2006). For supergiants with higher luminosity $\log(L/L_{\odot}) \gtrsim 5.8$ and for giants the mass-loss rates derived from observations are on average only slightly higher than predicted ones. This indicates only medium level of clumping in these stars. On the other hand, the mass-loss rates derived from observations are significantly higher than predictions for low-luminosity supergiants $\log(L/L_{\odot}) \lesssim 5.8$, pointing to a more significant level of clumping in their winds. However, in general the predicted mass-loss rates are not higher than those derived from the ρ^2 diagnostics. Consequently, even in this case the predictions do not contradict the observations.

**Figure 5.** Comparison of upper limits to the mass-loss rates from ρ^2 diagnostics (Puls et al. 2006) with our predicted dependence of mass-loss rates Eq. (1) as a function of stellar luminosity.

7 CONCLUSIONS

We tested the influence of XUV radiation on P V ionization fractions in hot star winds. Using hydrodynamical NLTE wind modelling we confirmed the conclusion of Waldron & Cassinelli (2010) that the XUV radiation may decrease the P V ionization fraction. As the result of various ionization and recombination processes, the P V ionization fraction in hot star winds does not come close to the value of 1, implying that the role of the P V lines as mass-loss rate indicators in hot star winds is not so straightforward. On the other hand, the large amount of XUV radiation necessary to significantly lower the P V ionization fraction to the values implied by observations leads to a decrease of the wind terminal velocity due to inefficient line driving. This contradicts the observations. Moreover, the wind clumping has an opposite effect than the XUV emission decreasing the wind ionization. Consequently, it is unlikely that the effect of lowering the P V ionization fraction by XUV radiation alone can bring the theory and observations in accord.

We also provide a useful mass-loss rate formula and compare it with other mass-loss rate diagnostics. We show that for supergiants and giants this formula passes two important observational tests against mass-loss rates derived from X-ray line profiles and ρ^2 diagnostics. This supports the reliability of mass-loss rates predictions derived from modern wind codes for luminous hot stars.

For main-sequence stars the predicted mass-loss rates are sig-

nificantly higher than those inferred from the P v or X-ray lines. This may indicate that the "weak wind problem" recently detected in low-luminosity main-sequence stars occurs to some extent also for the stars with higher luminosity. While the explanation of this "weak wind problem" for low-luminosity main-sequence stars is at hand (too large cooling length, Lucy & White 1980, Martins et al. 2005b, Cohen et al. 2008, Krtićka & Kubát 2009, Lucy 2012, or influence of X-rays on the mass-loss rate, Drew et al. 1994) such explanation valid for all main-sequence stars with any luminosity is currently missing.

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